The origin of cosmic rays: Explosions of massive stars with magnetic winds and their supernova mechanism

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ABSTRACT

One prediction of particle acceleration in the supernova remnants in the magnetic wind of exploding Wolf Rayet and Red Super Giant stars is that the final spectrum is a

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composition of a spectrum $E^{-7/3}$ and a polar cap component of E^{-2} at the source. This polar cap component contributes to the total energy content with only a few percent, but dominates the spectrum at higher energy. The sum of both components gives spectra which curve upwards. The upturn was predicted to occur always at the same rigidity. An additional component of cosmic rays from acceleration by supernovae exploding into the Inter-Stellar Medium (ISM) adds another component for Hydrogen and for Helium. After transport the predicted spectra $J(E)$ for the wind-SN cosmic rays are $E^{-8/3}$ and $E^{-7/3}$; the sum leads to an upturn from the steeper spectrum. An upturn has now been seen. Here, we test the observations against the predictions, and show that the observed properties are consistent with the predictions. Hydrogen can be shown to also have a noticeable wind-SN-component. The observation of the upturn in the heavy element spectra being compatible with the same rigidity for all heavy elements supports the magneto-rotational mechanism for these supernovae. This interpretation predicts the observed upturn to continue to curve upwards and approach the $E^{-7/3}$ spectrum. If confirmed, this would strengthen the case that supernovae of very massive stars with magnetic winds are important sources of Galactic cosmic rays.

1. Introduction

Since 2008 there has been increasing evidence for an extra component of cosmic ray electrons and positrons, with a plateau of cosmic ray electrons showing an E^{-3} spectrum, and the CR-positron/electron ratio approaching $E^{+1/3}$ (ATIC: Chang et al. 2008; Pamela: Adriani et al. 2009). These results confirm a quantitative model originally proposed in 1993 (Stanev et al. 1993), in which the supernova shock racing through a magnetic wind (Biermann 1951, Parker 1958) gives rise to a source spectrum of E^{-2} from the polar cap of the star, where the magnetic field is radial, and $E^{-7/3}$ from most of 4π, where the magnetic field is nearly circular (Biermann 1993). Allowing for losses (Kardashev 1962) the polar cap component spectrum becomes E^{-3} for observers of cosmic ray electrons. Since acceleration is slower for a radial magnetic field (Jokipii 1987; Meli & Quenby 2003a, b; Ellison & Double 2004; Meli & Biermann 2006) than for a tangential magnetic field, more secondaries are produced in the polar cap region, any resulting secondary spectrum is shifted down in energy and up in flux thus explaining the observations (Biermann et al. 2009b).

The prediction of the E^{-3} cosmic ray electron component was confirmed (HESS: Aharonian et al. 2009) with a spectrum of $E^{-3.1\pm0.1(stat.)\pm0.4(syst.)}$. This approach has also led to an understanding of the WMAP haze (Finkbeiner 2004; Hooper et al. 2007) with a predicted spectral behavior of $\nu^{-2/3}$, ν^{-1}, and $\nu^{-3/2}$ (Biermann et al. 2010). This prediction is consistent with the detection of the Inverse Compton component of the WMAP haze, the Fermi haze and its spectrum (Dobler et al. 2010; Su et al., 2010). These spectral index predictions are derived from the assumption, that a diffusive regime in a disk connects to a convective regime in a magnetic wind for cosmic ray transport. Thus, several independent observations support the quantitative model proposed in 1993 (Stanev et al. 1993) of massive star explosions. The original cosmic ray spectra are consistent will all these new observations.

There are a number of ideas that have suggested an upturn in the cosmic ray spectra, such as a nearby source or substructure in the accelerating shocks. Here, we focus on the upturn of the spectra predicted in 1993 (Biermann 1993, Stanev et al. 1993, parallel papers are summarized in Biermann 1994).

It had been proposed (see also Prantzos 1984, 1991, 2010; Völk & Biermann 1988) that the origin of cosmic rays can be traced to three source components: a) The cosmic rays originating from supernovae exploding into the ISM; b) The cosmic rays from supernovae exploding into red supergiant (RSG) winds; and c) The cosmic rays from supernovae exploding into blue supergiant or Wolf Rayet (WR) star winds. Disregarding the possible binary character of the stars, this is essentially a mass sequence, and a key property of these stellar winds is that they are magnetic (Abbott et al. 1984; Barvainis et al. 1987; Drake et al. 1987; Churchwell et al. 1992). As Parker (1958) showed, the asymptotic magnetic field topology is radial in a polar cap, and tangential over most of 4π. Furthermore, observations of these stars and their interpretation (e.g. Woosley et al. 2002, Heger et al. 2003) show that the wind eats back down into the star, and so the abundances in the RSG star winds are enriched in Helium, and those of WR stars are concentrated in Carbon and

Oxygen. Therefore it can be expected, that in cosmic rays at higher energy much of the Helium can be traced to these winds of RSG stars, and possibly all of the elements heavier than Carbon to the WR stars (Stanev et al. 1993, Biermann 1994).

We use here the concept that interstellar transport (e.g., Rickett 1977) is governed by a Kolmogorov spectrum (Kolmogorov 1941a, b, c), as discussed in Biermann (1993), and Biermann et al. (2001). We test this prediction with new data (CREAM: Seo et al. 2008; Ahn et al. 2009, 2010). The data are shown to be consistent with the prediction of 1993, and so we propose further tests.

2. The upturn observed in cosmic ray spectra

The general concept developed in 1993 is that, after transport is allowed for, the spectra are composed of a sum of a $E^{-8/3}$ component, and a $E^{-7/3}$ polar cap component, which is at a level of a few percent in integrated power. These components run up to the knee energy, with about $Z\,10^{15}$ eV, where the polar cap component cuts off completely, and the main component turns steeper, at about $E^{-3.15}$ (Biermann 1994, Biermann et al. 2005). The spectrum finally cuts off completely at about $Z\,10^{17}$ eV. Here Z is the charge of the cosmic ray nucleus.

It is not obvious a priori, whether RSG star winds should have the same properties in terms of their magnetic field as WR star winds: It is not clear, as to whether the energy fraction of the polar cap component is the same for both, and also whether the characteristic knee rigidity ratio is the same. However, for simplicity we will assume that the population energy fraction and the knee particle energy are the same for both kinds of stars until the data force us to accept otherwise.

We first deal with all elements from Carbon (C) through Iron (Fe) and with the combined data as a function of energy/nucleon. Next we deal with Helium, and test whether the same numbers can describe its spectrum. Finally we deal with Hydrogen, which does have a major ISM-SN

contribution. In our 1993 prediction Hydrogen had a cross-over with Helium, when the spectra are plotted as a function of energy per particle, which is confirmed now. We also test whether Helium or any other elements also require an ISM component to understand its spectrum.

2.1.   Carbon through Iron

The Ahn et al. (2010) data are plotted as $E_n^{5/2} J(E_n)$, where E_n is the energy per nucleon. Since the prediction is that $J(E_n)$ is the sum of one component with $E_n^{-8/3}$ and the polar cap component with $E_n^{-7/3}$, we note that the product $E_n^{5/2} (E_n^{-8/3} + E_n^{-7/3})$ is a symmetric shallow near-parabola, with the break at the energy $E_{n,m}$, where the two contributions have equal flux. Fitting the shape of this function involves one parameter, that energy per nucleon at the break energy $E_{n,m}$.

First of all, the spectra before the break are determined by CREAM (Ahn et al. 2009) to be $E^{-2.66\pm0.04}$, to be compared with the 1993 prediction of $E^{-8/3-0.02\pm0.02}$, with an asymmetric predicted error distribution. The 2009 determination is reasonably close to the prediction, as the difference is only 0.007 plus the corresponding errors. So we stick with $E_n^{-8/3}$. The cosmic ray electron data suggest in turn, that at source E^{-2} is a good fit for the polar cap component, and so we also stick with $E_n^{-7/3}$ after transport.

Fitting this to the curves of the elements reveals that the break energy $E_{n,m}$ is consistent with being the same for all these elements.

The fit curve $E_n^{5/2} (E_n^{-8/3} + E_n^{-7/3})$ to the plot demonstrates, that a break energy of 10 TeV/N is consistent with the data. The present data are in fact compatible also with 3 or 30 TeV/N to within the errors, but 10 TeV/N is the best common fit. The 1993 arguments gave 12 TeV/N, derived from a fit to overall air shower data, at vertical and slanted zenith angles.

We show in Fig. 1 the fits of all elements heavier than Hydrogen compared to experimental

data.

2.2. Helium and Hydrogen

Measured in flux per energy/particle Helium crosses over Hydrogen near about 10 TeV. The specific spectral index of the ISM-contribution has to be determined best by the Hydrogen component, and that approaches $E^{-2.78\pm0.009}$ for protons at low energy (AMS: Alcaraz et al. 2000). Since there is a slight flattening due to the wind-component, we need to adopt a spectrum for the ISM-component, originally predicted to be $E^{-2.75\pm0.04}$, for which we write more generally $E^{-p_{ISM}}$.

Fitting then $E_n^{5/2}\,(E_n^{-8/3} + E_n^{-7/3} + b\,E_n^{-p_{ISM}})$ gives us an estimate of the ISM contribution. We show the fit for H in Fig 2.2, and for comparison repeat the fit for He.

Fitting the data (from AMS: Alcaraz et al. 2000) gives at higher energy a spectral index of 2.66 ± 0.02, This suggests that the ISM contribution has $p_{ISM} \simeq 2.80$ and then corresponds to $b_H \simeq 1$ for Hydrogen at the steeper spectral index 2.80, and about $b_H \simeq 4$ for the slightly flatter index of 2.75. This corresponds to a wind-contribution of the energetics for CR-Hydrogen of 25 % for the steeper index, and about 12 % for the slightly flatter index. Using $p_{ISM} = 2.70$ does not give a satisfactory fit to the Hydrogen data. The differences illustrate the uncertainties. For Helium the ISM-CR component is very much smaller, and hard to define within the errors, using data from independent instruments.

The largest modification with respect to 1993 is the slightly larger contribution of the wind component to Hydrogen.

2.3. Differential spectra

Differential spectra are shown in Ahn et al. (2009). All of those show near constant ratios, with the exception of Nitrogen: The Nitrogen/Oxygen ratio shows a weak dependence, consistent
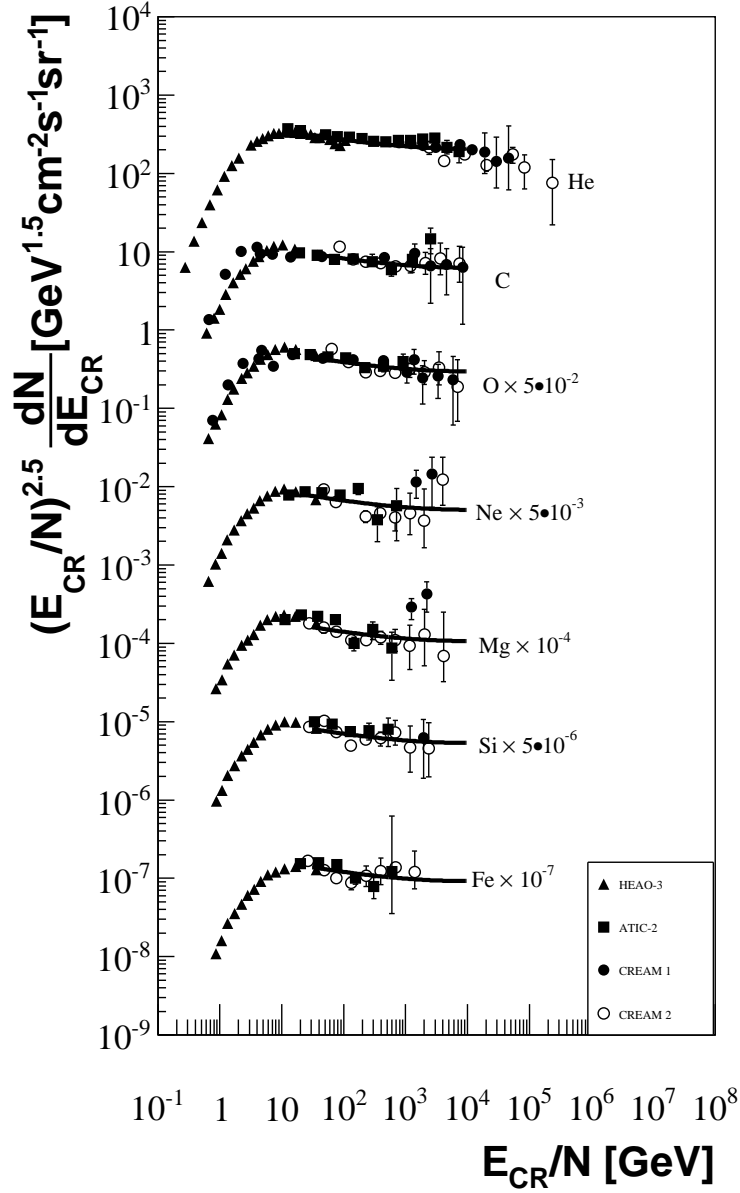
Fig. 1.— Fit for elements heavier than H with the spectral shape from Stanev et al. (1993). We use for the break energy 10 TeV/N and only fit the fluxes above 50 GeV/N because of solar modulation and low energy spallation effects. No ISM-SN CR-component is necessary to fit the spectra. Lower energy data implies a small ISM-SN CR component for He.
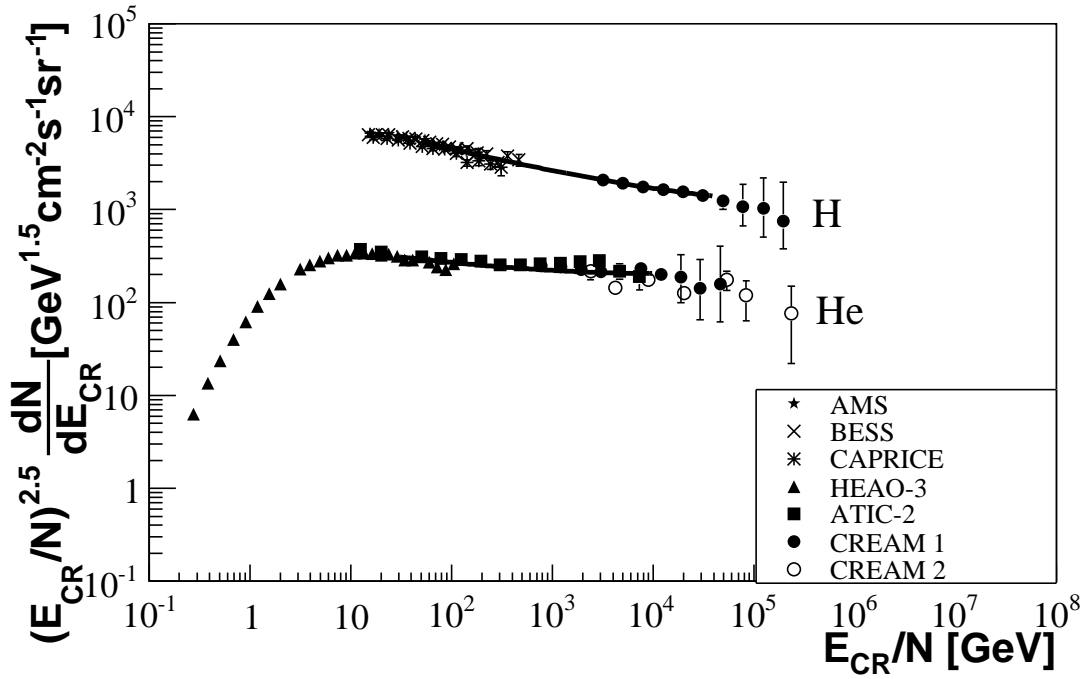
Fig. 2.— Fit to proton and Helium data with spectral shape given in Stanev et al. (1993). For He we use for the break energy 10 TeV/N, and for H 20 TeV, since the rigidity E/Z is given. For H the strongest component is from ISM-SN, a wind-component is required to fit the data, but is weaker. Replotting these spectra in energy per particle would shift He up by a factor of 8 and to the right by a factor of 4, at 10 TeV/N, and so give the cross-over near that energy with Hydrogen.

with $E^{-5/9}$ suggesting interaction in an environment of a massive wind-shell, where the spectrum of magnetic irregularities excited by cosmic ray particles themselves dominates over other spectra (Biermann 1998; Biermann et al. 2001, 2009b).

The Iron/Oxygen ratio shows a weak increase consistent with weak differential spallation: Low energy Fe has stronger spallation, so less iron is left. If this is the true interpretation, then at higher energy the ratio should approach a constant. The numbers suggest that up to about half of the low energy iron is lost through spallation.

2.4. Supernova mechanism

The rather remarkable observation, that this break energy $E_{n,m}$, where the $E^{-8/3}$ and the polar cap component $E^{-7/3}$ have equal fluxes, is well defined, even if not precisely known, immediately shows that all participating supernovae appear to approach asymptotically a commonality of correlated magnetic field strength and explosion energy (Biermann 1993). Stellar evolution of massive stars (see, e.g., Woosley et al. 2002) suggests, that indeed a commonality of properties in their asymptotic state might well be quite plausible. Using the Parker limit (Parker 1958) for a tangential azimuthal magnetic field this requires $B_\phi(r)\,r\,U_{SN}^2$ to be the same for all such supernovae, and since in this limit $B_\phi(r)\,r$ is a constant, using the base of that regime r_s requires $B_{\phi,s}\,r_s\,U_{SN}^2$ to be the same; here U_{SN} is the shock speed of the supernova racing through the wind, and $B_\phi \sim 1/r$ is the azimuthal magnetic field. Assuming that the mass ejected is similar this connects the explosion energy directly to the magnetic field strength. The only mechanism that does that is the magneto-rotational mechanism (Kardashev 1964, Bisnovatyi-Kogan 1970, Bisnovatyi-Kogan & Moiseenko 2008, Moiseenko et al. 2010). One could speculate that the neutrinos couple to the exploded magnetized outflow through instabilities and irregularities, and so enhance the explosion just as photons can couple better to a wind in early type stars since the wave speed in a magnetic wind is higher (Seemann & Biermann 1997); thus it is conceivable that neutrinos play a

concomitant role in the explosion mechanism (see, e.g., Woosley et al. 2002).

Since this mechanism employs rotation and magnetic field to their limits, this mechanism also gives rise to the axial symmetry seen in some supernova explosions and required by Gamma Ray Bursts (GRBs). So it is tempting to speculate that this is in fact the same mechanism that leads to supernovae and GRBs.

2.5. Higher cosmic ray energies

The sum of all these spectra should obey the observed total spectra of particles determined in other ways. This should be consistent with the overall spectra all through EeV energies. This test was used in 1993, and now, with increased H and He wind-contributions, can be done again. Using the new data increased the Hydrogen and Helium wind contribution, and so we may have to decrease the break energy by a small amount to compensate in the total from the knee and beyond.

We note that the particles near the knee, here with a notable contribution also from Hydrogen and Helium, may constitute the seed particles for the next step up in energy, when a relativistic shock (Gallant & Achterberg 1999) may push the entire spectrum up by a considerable factor. Ultra high energy cosmic rays could be drawn from a strongly enriched composition (Biermann et al. 2009a, Gopal-Krishna et al. 2010). With such a concept the results here suggest that in different parts of the sky, ultra high energy cosmic rays might be dominated by low mass and very high mass elements (Abbasi et al. 2009; Abraham et al. 2010).

3. Conclusions

Here we demonstrate that the upturn recently observed in cosmic ray spectra matches the quantitative predictions from 1993. As now a number of independent observations (CR-positrons, CR-electrons, WMAP haze, Fermi haze, the 511 keV line emission from the Galactic Center region,

and the CR-upturn observed by CREAM) have been shown to be consistent with the original quantitative proposal (Stanev et al. 1993), the implications originally suggested find support as well.

Since the upturn is consistent with being at the same energy/charge ratio for all heavy elements, and clearly very nearly the same for the very large number of participating supernovae, this finding supports the magneto-rotational mechanism for massive star explosions (originally proposed by Bisnovatyi-Kogan 1970; see also Biermann 1993). Only if energy and magnetic field of the exploding star are strongly correlated, can such a characteristic feature in the observed cosmic ray spectrum be the same for all such stars, whose explosions contribute to the cosmic rays at high energy.

A clear prediction is that the upturn should continue to approach asymptotically a spectrum of $E^{-7/3}$.

As so often, much better data, extending to yet higher energy, will allow to refine and test the concept at yet higher accuracy.

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